SUMMARY OF "GUIDELINES FOR DYNAMIC DATA ACQUISITION AND ANALYSIS"

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A 325-page Guidelines document [1], whose objectives are to increase the accuracy and reduce the errors and variability commonly found in the measurement of structural shock and vibration and of acoustic and aerodynamic noise, was recently submitted to the Air Force Space and Missile Systems Center. The Guidelines are divided into five sections: (1) Scope, (2) Dynamic Measurement Planning, (3) Data Acquisition, (4) Data Validation and Editing, and (5) Data Analysis; plus appendices cm two current state-of-the-art topics: (A) Pyroshock Data Acquisition and Analysis, and (B) Nonstationary Random Vibro-acoustic Data Analysis. Each section is separately summarized, with the appendices receiving special emphasis.

INTRODUCTION

Over a very long period of time (in excess of two decades), Air Force personnel have observed a seemingly endless series of errors and anomalies in the acquisition and analysis of structural dynamic and aeroacoustic data, For example, Figure 1 shows a comparison of spectral analyses performed by three contractors on the same measurement of Shuttle random vibration flight data. Data scatter in excess of 30 dB observed at some frequencies is obviously unsatisfactory, To further assess the magnitude of this problem, a data analysis "round robin" was later arranged by personnel from The Aerospace Corporation (TAC), who are technical advisors to the Air Force Space and Missile Systems Center and its preceding organizations. Identical magnetic tape dubs of short time-limited stationary random signals were sent to several data processing centers that were requested to perform 1/3 octave band analyses with their normally-used equipment, and return the analyses to TAC [2]. The resulting excessive data scatter is shown in Figure 2. Rather than continue to accept this situation in perpetuity, three TAC personnel (Chuck Moening, Carole Tanner, and Don

Wong) suggested that the Air Force fund the development of Guidelines that would help to reduce the variability and eliminate the errors commonly found in dynamic data acquisition and analysis.

JPL was selected to prepare the Guidelines, along with any research studies required to achieve the Guidelines objectives. Harry Himelblau, who was then recently employed by JPL after years of aerospace dynamics experience elsewhere, was appointed Task Manager of the team. Allan Piersol was brought onboard because of his acknowledged expertise in data analysis and his prior affiliations with JPL on a variety of dynamic state-of-the-art studies. Jim Wise of JPL also joined the team, adding his expertise in data acquisition systems. This left one weakness in the knowledge base, that of the utilization of telemetry systems for the remote transmission of dynamic data. This gap was filled by Max Grundvig, brought out of retirement from TAC for this assignment.

Because of the enormity of preparing such broad ranging Guidelines, it was initially recognized that even four experienced authors would be unable to know all the critical details needed for inclusion in this type of document. Thus a call went out to experts everywhere to voluntarily review the Guidelines during its various stages of development and to fill in important omissions. Both gladly anti sadly, the authors acknowledged the nearly limitless number of improvements needed in the document. For their part, the reviewers were very tolerant with the authors as the deficiencies in the Guidelines were identified and were very generous with their time in getting the deficiencies removed. Near the end of the review process, a three-day seminar was held at TAC to expedite final resolution of problems remaining with the Guidelines. Meanwhile, TAC personnel and JPL management witnessed this process with a combination of benign resignation and occasional exasperation.

The authors would be remiss if they did not identify a few of the major reviewers (in alphabetical order) and their organizations: Larry Bement and Jim Schoenster of NASA Langley, Bob Bohle of Kistler, Anthony Chu of Endevco, Charlie Coe of NASA Ames, John Favour and Clark Beck of Boeing, Dennis Foti of Metrum, Arnold Galef, George Scott, Chuck Wright and Glenn Wasz of TRW, Gerry Kahre, Paul Spas, Dan Powers, Marc Hoskins and Dave Sherry of McDonnell Douglas, Ron Merritt of NWC/China Lake, Jim Nagy of NATC/Patuxent, Dennis Nelson of Sandia, Pete Rentz of Syscon, Karl Siwiecki and Jim Lally of PCB, Strether Smith and Bill Hollowell of Lockheed, Vlad Valentekovich of Wyle, Joe Weatherstone and Bill Brennan of B&K, and Scott Walton of the Army Combat Test Activity. Some reviewers read every word of several drafts, while others concentrated on sections that embodied their areas of expertise. Some furnished illustrations previously unknown to the authors, whereas others performed research to resolve controversial technical issues. Although not identified here, other reviewers made significant though less comprehensive suggestions. All made substantial contributions to the list of references, which is considered the heart of the Guidelines.

One of the first tasks was to decide how to subdivide. the wealth of material into sections. Two of these sections were obvious: Data Acquisition, and Data Analysis. A preceding Scope was needed to provide the purpose or objectives, and to list the topics to be excluded (mainly to limit the cost and size of the document), Inadequate planning was identified by most authors and reviewers as a primary cause of bad data. Thus a section on Measurement Planning was added, following the Scope, to emphasize its importance. It was pointed out that, due to advances in digital data processing, it had become practical to remove certain types of data acquisition errors through editing. Thus a section was added on Data Validation and Editing (between sections on Data Acquisition and Data Analysis) to encourage the use of these techniques. A state-of-the-art appraisal showed that two "unsolved" measurement problems remain in the field of dynamic data acquisition and analysis, namely, near-field measurement of pyroshock, and the analysis of nonstationary random data, In order to give these problems special attention, each was discussed in a separate appendix. Each section is summarized in the following paragraphs,

SCOPE

After a statement of objectives, listed in the abstract, the utilization of the Guidelines for dynamic measurements on aerospace, sea and ground transportation vehicles, machinery and civil engineering structures was recommended. Specifically excluded from the Guidelines were data from modal tests, power, intensity and mechanical impedance measurements, equipment health monitoring, and biodynamics, hearing and speech measurements.

DYNAMIC MEASUREMENT' PLANNING

Planning topics include the types, number, locations and directions of the transducers, the frequency and dynamic ranges of the instrumentation, measurement durations, instrument hardware and software selection considerations, vendor evaluation, time code utilization, special considerations for making multi-channel measurements, and the importance of developing an application-dependent error budget. Seven "deadly sins" were listed at the end of this section, i.e., mistakes most commonly encountered in dynamic data acquisition and analysis, which have been later expanded to ten!

DATA ACQUISITION

Dynamic data acquisition can be a very complicated process because of several different factors. First, there are many different paths by which signals can be transmitted from the transducers to the data recorders. Figure 3 attempts 'to show the majority of these paths for a variety of typical aerospace applications. (The numbers in parentheses in this figure refer to subsection numbers.) Second, there are a large number of ways that modern transducers generate their electrical signals under dynamic excitation. Third, there are many different environments and conditions that may cause unwanted transducer outputs and distortions, besides the intended form of dynamic excitation. Fourth, there are a wide variety of characteristics that should be thoroughly understood before other instruments, identified by the boxes of Figure 3, are selected or utilized. Recommendations are made throughout this section to avoid specific measurement problems.

In many cases, the transducer cannot be adequately protected against other environments without compromising its intended performance, whereas the various electrical instruments can be and usually are protected from these outside influences. After the basic design features (usually the ideal single-degree-of-freedom) and material properties of transducers are reviewed, much of this section is devoted to the effects of various environments on accelerometers, pressure transducers, force and strain gages. Many examples are given as warnings to the unwary or uninformed user of what might happen if care is not taken in the selection and utilization of transducers.

After a fairly rigorous summary of transducers issues, a similar summary was made of the various other instruments of the Data Acquisition system. These include signal conditioners, power supplies, filters, cabling, land lines and telemetry, multiplexer (muxes) and demultiplexers (demuxes), analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), and a variety of data recorders, Many of these instruments may not be required for certain applications such as laboratory and ground testing. Fewer examples are needed for these electronic instruments than for transducers.

To encourage competition for some of the more expensive instruments, such as muxes and demuxes, telemetry and tape recorders, the national flight and ground test ranges set up the Inter-Range Instrumentation Group (IRIG) to write standards whose primary objective is to limit the cost of these instruments [3]. Rather than survey the wide variety of instruments available in these categories, this section simply summarizes the IRIG standards. However, one known consequence of these standards is that they often cause a delay in the development of improved instruments.

This section concludes with recommendations for instrument and system calibrations, setting system gain factors, and a check list for record keeping.

DATA VALIDATION AND EDITING

One of the most overlooked requirements for a successful dynamic data acquisition and analysis program is a comprehensive review of all acquired data signals for anomalies, and either the elimination of anomalous signals or their correction by appropriate editing procedures prior to detailed data analysis operations. The specific procedures to validate and edit dynamic signals covered by this section are outlined in Figure 4 (the numbers in parentheses refer to subsection numbers). It is emphasized that the various validation procedures listed in Figure 4 should not replace more qualitative evaluation procedures that may have been perfected through past experience, e.g., talented technicians can often detect even subtle anomalies in measured vibration and acoustic signals by simply listening to the signals through a head-set. Also, the automation of the data validation procedures using “expert” computer programs is recommended as long as an experienced analyst is available to review the results.

It is seen in Figure 4 that a classification of the measured dynamic signals (random versus periodic and stationary versus time-varying) is recommended as a first step in data validation and editing, since the necessary validation procedures are often heavily influenced by these basic characteristics of the data. Detailed statistical techniques to (a) identify periodic components in otherwise random signals, and (b) to detect nonstationary trends in signals, are presented to assist this data classification effort. When the signals are measured and recorded in analog form, a visual inspection of analog time histories for six common anomalies is recommended as a first step in data validation, For those cases where the original data are acquired and recorded in a digital format, or analog signals are converted to a digital format prior to analysis, a visual inspection of digital time histories is also recommended. Certain types of data anomalies (clipping, excessive instrumentation noise, intermittent noise, and signal drop-outs) can also be detected by a careful inspection of probability density and narrowband spectral plots. Such evaluations of analyzed data are mandatory when the signals are analyzed on-line, but are also recommended as a backup evaluation even when analog and/or digital time histories are available for inspection. For each inspection procedure and type of anomaly, this section details (a) an identification procedure and (b) a data rejection criterion. The identification procedure in each case is illustrated for (a) a periodic signal, (b) a stationary random signal, and (c) a transient signal.

Certain types of anomalies in acquired dynamic data are too destructive to allow the recovery of any meaningful information (e.g., extreme signal clipping). For many anomalies, however, meaningful information can be recovered by corrective data editing operations, if they are carefully executed. This section details and illustrates such corrective editing operations for (a) excessive instrumentation noise, (b) intermittent noise spikes and digital converter induced wild points, (c) spurious trends, and (d) temporary signal drop-outs. Again, these data validation and editing operations constitute an essential preliminary step prior to detailed data analysis.

DATA ANA] .YSIS

The analysis procedures covered by this section are outlined in Figure 5 (the numbers in parentheses refer to subsection numbers). This section starts with a summary of overall signal analysis procedures including (a) recording instantaneous values, (b) computing average values, (c) synchronous averaging procedures, and (d) signal filtering. This summary is followed by a discussion of signal properties that influence the type of data analysis procedure that should be used, specifically, (a) time dependence, (b) randomness, and (c) normality (Gaussianity). A procedure to distinguish between transient and nonstationary signals from a data analysis viewpoint is detailed. The appropriate data analysis procedures for three categories of signals are then detailed, namely, (a) individually measured periodic and random signals, (b) transient signals, and (c) two or more simultaneously measured random signals, The section concludes with a brief summary of references for other specialized data analysis procedures, e.g., parametric spectral analysis techniques. Specialized data analysis procedures for pyroshock and nonstationary random aeroacoustic and vibration data are presented in two separate appendices to the Guidelines.

The major emphasis in this section is on spectral analysis techniques using FFT algorithms. For each spectra] analysis procedure, recommendations are presented for the following: (a) computational algorithm, (b) instruments and software, (c) anti-aliasing filters, (d) leakage and tapering, (e) frequency resolution, (f) resolution error corrections, (g) statistical sampling errors, (h) overlapped processing, (i) zoom transforms, and (j) plotting. The subsection on shock response spectral analysis for transient data further discusses and makes recommendations concerning (a) digital sampling rate, (b) truncation errors, and (c) initial conditions. The subsection on dual channel analyses further discusses and makes recommendations concerning (a) time delay bias errors and (b) multiple path (reverberation) bias errors. All errors are detailed in easily used plots.

PYROSHOCK DATA ACQUISITION AND ANALYSIS

State-of-the-art problems associated with the measurement of near-field shocks from explosive devices are thoroughly discussed in this appendix. Specifically, the unique problems created by pyroshock signals are detailed for (a) transducers, (b) signal conditioners, (c) electrical lowpass filters, (d) mechanical lowpass filters, (e) data recorders and storage, (f) anti-aliasing filters and analog-to-digital converters, and (g) analysis procedures. These discussions arc followed by a summary of specific recommendations for the acquisition and analysis of pyroshock data. Emphasis is given to special data validation procedures, which are over and above those procedures for general dynamic data detailed in the earlier Data Validation and Editing section. Many of the discussions of pyroshock data acquisition and analysis problems have been previously published [4], as have been the specific recommendations presented in this appendix [S,6].

NONSTATIONARY RANDOM VIBROACOUSTIC DATA ANALYSIS

The random vibration environment of a space vehicle during launch is due primarily to aeroacoustic excitations during three events: (a) the acoustic noise during lift-off, (b) the shock-wave boundary-layer interactions during flight through the transonic speed range, and (c) the turbulent boundary-layer pressures during flight through maximum dynamic pressure. The average properties of these forcing functions and the aeroacoustic and vibration data they produce are time-varying (nonstationary) and, hence, cannot be rigorously analyzed as stationary random signals. On the other hand, the time variations are sufficiently slow to allow the structures and equipment subjected to the aeroacoustic and vibration loads to fully respond at any time during the nonstationary events, i.e., the excitations are too long in duration to be considered transients. This means that the maximum spectral values of the acoustic and vibration loads during each event can be used as criteria for acoustic or vibration tests using stationary random excitations, where the test spectrum value at each frequency conservatively represents the maximum spectrum value that occurred during the simulated nonstationary event (often referred to as a maximax spectrum).

This appendix discusses procedures for computing an equivalent stationary spectrum (a maximax spectrum) for nonstationary random data, and recommends specific frequency resolution bandwidths and averaging times for the analysis of Shuttle and Titan IV lift-off acoustic noise and vibration data. Detailed procedures to arrive at appropriate analysis parameters for more general nonstationary data are also presented. Early studies to arrive at appropriate procedures for the analysis of space vehicle launch acoustic and vibration data concentrated on parametric techniques applicable only to specific types of nonstationary signals [7,8]. However, these parametric procedures have been replaced in this appendix by more general procedures that involve the computation of a time-varying spectrum using a running average, from which a maximax spectrum can be determined, The optimum averaging time for the computation of 1/3 octave band spectra for nonstationary random acoustic data recommended in this appendix is designed to minimize the total mean square error in the maximum sound level estimates for a given nonstationary event, and is based upon derivations in [9,10]. The optimum frequency resolution bandwidth and averaging time for the computation of autospectra for nonstationary random vibration data also are designed to minimize the total mean square error in the maximum autospectra estimates for a given nonstationary event, and are based upon derivations in [9,10], which are further evaluated in the paper, "Optimum Parameters for the Spectral Analysis of Nonstationary Random Vibration Data," published in these proceedings.

SUMMARY

As the final topic to this paper, it might be appropriate to review the ten "deadly sins" listed at the end of the section on Measurement Planning, i.e., the major sources of error commonly found in dynamic data acquisition and analysis:

(1) No end-to-end calibration, especially important in flight and major ground tests, permitting a large number of potential error sources to influence the determination of instrumentation calibration factors.

(2) Advanced purchase of a large number of incorrectly-set unadjustable fixed-gain amplifiers, resulting in uncorrectable cases of signal loss due to saturation, or serious contamination by background noise.

(3) Ignoring the effects of non-dynamic environments and other dynamic loads on dynamic transducers and signal conditioners, such as base bending of accelerometers, vibration response of microphones, and moisture penetration into signal conditioners, causing unknown errors in the measured output.

(4) Failure to properly evaluate the effects of the installation or mounting on the transducer response to the dynamic load or environment to be measured, causing an erroneous output.

(5) Locating low pass filters after signal conditioners, rather than ahead of them, allowing high frequency components to saturate the conditioners and invalidate the data at all frequencies.

(6) Lack of an anti-aliasing filter prior to analog-to-digital conversion, leading to Nyquist foldover, despite all warnings to the contrary.

(7) When nonstationary flight data are analyzed, the initiation of time windows manually by data processing personnel rather than by a time code-activated switch, resulting in erroneous spectra caused by uncontrollable time translations.

(8) Selecting a frequency resolution bandwidth wider than structural resonant bandwidths in random vibration data analysis, causing significant errors in the accurate determination of spectral peaks.

(9) Making pyroshock accelerometer measurements too close to the pyrotechnic source, allowing intense high frequency response components, including a possible accelerometer resonant response, to saturate the transducer and/or signal conditioner, and invalidate the resulting data at all frequencies.

(10) Human errors, often due to the lack of proper planning, training, communication, attention to details, and/or personal motivation in the data acquisition and analysis process, which can often be circumvented by direct user involvement in all aspects of these activities. One possible solution to this problem is to put all measurement functions, from instrument selection through processing data plots, under one organization made responsible by management for the accuracy of resulting data.

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